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A Method for Concept Exploration of Hypersonic Vehicles in the Presence of Open & Evolving Requirements

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ABSTRACT

Several unique aspects of the design of hypersonic aerospace systems necessitate a truly multidisciplinary approach from the outset of the program. These coupled with a vague or changing requirements environment, provide an impetus for the development of a systematic and unified approach for the exploration and evaluation of alternative hypersonic vehicle concepts. The method formulated and outlined in this paper is founded upon non-deterministic conceptual & preliminary design formulations introduced over the past decade and introduces the concept of viewing system level requirements in a similar manner. The proposed method is then implemented for the concept exploration and design of a Hypersonic Strike Fighter in the presence of ambiguous open and/or evolving requirements.

INTRODUCTION

Most commonly used approaches to conceptual design today start with a fixed set of requirements, and synthesize and size various concepts, using either deterministic or probabilistic methods, to achieve the final optimal vehicle design. This approach, however, does not always yield the most affordable vehicle. In many cases, the final performance and affordability of a given aircraft is predetermined the moment the system requirements are defined and accepted. Further, it is often the case that the design requirements are not fixed but rather evolve through the development life of the vehicle. If these requirements are varied substantially, the design of the vehicle and the basic technology selection may have to change significantly to re-open the design space. A good example would involve the addition, as an afterthought, of a carrier compatibility requirement to a highly specialized land based aircraft design. Most likely, the designers would have never considered implementing the modularity or technologies necessary to achieve carrier compatibility in the initial vehicle design. Because of this, the addition of the carrier compatibility requirement (constraint) may render the system infeasible. Two potential approaches present themselves to solve this problem.

First, the engineer can evaluate the infusion of specific technologies into the existing design to increase the capability and open the feasible and viable design space. This approach generally lends to a compromised aircraft that is more expensive than the original design. Alternatively, a system may be redesigned from the ground up to implement the new mission requirements and constraints. The immediate disadvantage of this option is that this redesign effort usually consumes large amounts of time and money, and can easily produce cost overruns that can kill a program. Based on these two scenarios it is evident that an approach that will allow for the evaluation of the effect of varying requirements on the feasible and viable design space from the outset is desired. This was approached by Mavris and DeLaurentis in relation to the F-18 **[1]**. In this case, the requirements exploration space was modeled as a continuum. The baseline vehicle was altered parametrically and the responses were presented as deltas in requirements and concepts as a function of technologies. However, there are many instances where this is not the case. The requirements could change dramatically, causing discontinuous jumps in the behavior of the responses. This produced response variations with respect to not only the vehicle design variables, but also to the top-level requirements and incremental technology changes. This unified trade-off environment is illustrated in Figure 1. For cases where the evolving requirements space is not well behaved, an alternative approach to determining the effect of the program requirements on the system is necessary. This paper outlines one such method to assist the engineer in performing this operation. Subsequently, the method is illustrated using a notional Hypersonic Strike Fighter (HSF).

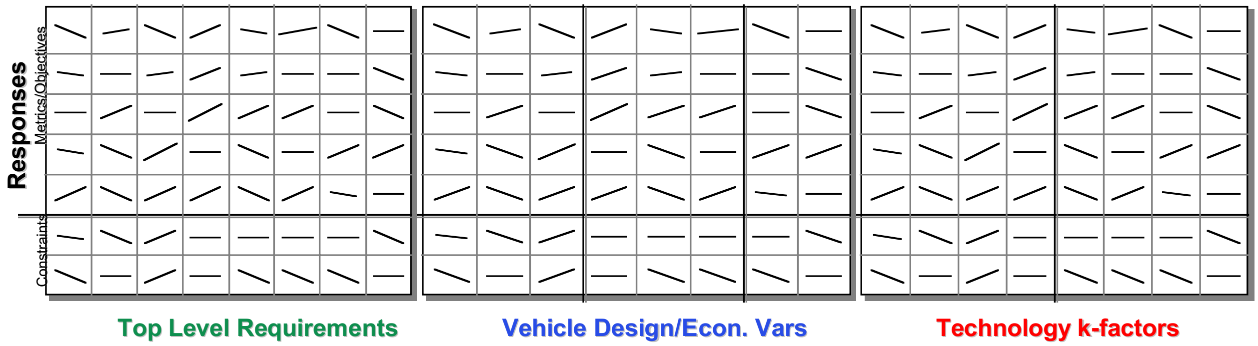

Figure 1: Unified Environment for Design Sensitivities [1]

METHODOLOGY

The methodology described and illustrated within this paper is typical of that used to create any complex system. However, properties associated with the HSF necessitate modifications that may not otherwise be apparent in the design of simpler vehicles. Figure 2 illustrates the flow of the proposed design process formulated in this paper.

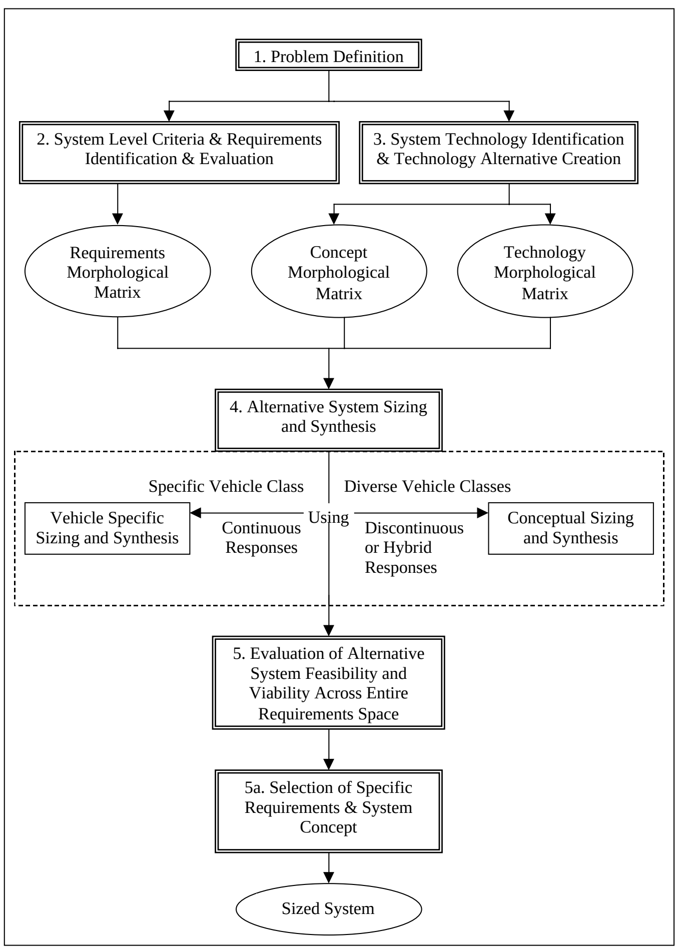

Figure 2: Hypersonic Vehicle Concept Exploration, Design, and Selection Flowchart

PROBLEM DEFINITION (STEP 1) – The first step in this methodology, as with any complex system design, is to determine what problem one is trying to address. In the case of the HSF, this task has been performed by the requesting agency. A representative request for proposal (RFP) specifies that a hypersonic weapons system is needed to strike "high-value, time-critical targets" at significant ranges **[2]**. The RFP is an unclassified version of the types of studies currently being undertaken by the armed services in response to needs assessed in the recent conflicts in Iraq, Bosnia, and Kosovo. One of the problems, first identified during the Gulf War, is that the current weapons systems were unable to strike targets such as Iraq's mobile Scud launchers. Therefore, systems that can respond quickly to the emergence of threats, with a minimal time to strike are needed.

SYSTEM LEVEL CRITERIA AND REQUIREMENTS IDENTIFICATION & SELECTION (STEP 2) – Identification and selection of which criteria best describe the weapons system effectiveness represents the next step in the proposed process. Furthermore, a taxonomy of the various requirements is undertaken, in addition to a determination of which ones could possibly be changed and which ones must remain fixed. Variability of the requirements needs to be monitored closely as it is not uncommon for the procuring agency to change the requirements of a program as it progresses through development. This has historically led to runaway development costs and compromised systems. Therefore, it is useful for the engineer to evaluate the effect of varying/evolving requirements on the feasible and viable design space of the vehicle. A method for this is illustrated in Figure 1. In the case of the HSF, the discontinuous nature of the responses necessitates a ground up methodology to analyze the effect of requirements changes. In this case, the requirements are treated at the same time the system level technologies and baseline vehicle are identified. This technique produces responses to both the requirements and the design variables, which include the multiple technology combinations.

The HSF RFP is an ideal test case in illustrating the need for a detailed analysis of the system requirements at the beginning of the program **[2]**. The system performance and affordability requirements were either not directly specified or given a wide range of acceptable values. Since some of the specific values of these requirements had the potential to produce vastly different aircraft, it is necessary to give the engineer a basic feel for what a change in each requirement could do to the specific aircraft. The RFP Requirements are given in Table I.

Carrier Compatibility - While the RFP only desired a carrier compatible vehicle, it required that an analysis be done as to what tradeoffs needed to be made to achieve carrier compatibility if the vehicle was not specifically designed to satisfy carrier compatibility. Further, the RFP listed some maximum vehicle dimensions and weights to achieve carrier compatibility. The RFP minimum requirements for carrier compatibility are given in Table II.

However, for an aircraft to be truly carrier compatible there are several other design limitations that come into effect. A good example is the use of cryogenic propellants. There is currently no capability on US aircraft carriers to supply liquid hydrogen or methane in the quantities needed to operate a fleet of cryogenically fueled HSF's. Further, the environment on a carrier is heavily corrosive; therefore, some of the high temperature materials that could be readily used on land based aircraft would become maintenance nightmares on aircraft carriers. Carrier aircraft are therefore significant design challenges, and the choice to implement carrier compatibility needs to be made at the beginning of the design process.

Creation of Requirements Matrix of Alternatives – To study the effect of a changing requirement space, it is helpful to develop a modified version of the Matrix of Alternatives or Morphological Matrix. Typically, this matrix consists of an array of various technology alternatives for different components of the system. However, in the case of the modified matrix the technologies are replaced with specific requirements values. An example, illustrating the requirements for an HSF, of this matrix is shown in Figure 3.

The requirements Morphological Matrix contains different, discrete values for each specific requirement class. In the case of the HSF, most of the requirements listed in the matrix yield continuous response spaces for a selected vehicle class; however, the take-off and landing requirements, and the loiter and time-to-target requirements are prime examples which would result in dramatically different configurations. The carrier compatibility desirement, not only affects the take-off and landing velocities, which are directly related to the field lengths required for a land based aircraft, it also places many other constraints upon the aircraft design.

Using the Requirements Morphological Matrix, it is possible to identify each of the permutations obtained from this large number of requirements scenarios. If the requirements are well behaved, the aircraft and technology combinations can be reduced dramatically by formulating them in a continuous fashion using a meta-model representation and subsequently discretizing them to determine specific combinations. These types of problems can only be treated continuously if the problem is reformulated at a level of abstraction that allows the evaluation of radically different concepts based on higher level attributes and references.

Table I: RFP Requirements

Requirement	Threshold	Desired
Cruise Speed	Mach 4	Mach 8
Mission Radius	750-nm	1500-nm
Max Speed at Sea Level	400-kts	630-kts
Design Weapon Payload	2 Adv. High Spd. Wpns.	8 Adv. High Spd. Wpns.
Alternate Weapon Payload 1	2 JASSMs or SLAM-ERs	8 JASSMs or SLAM-ERs
Alternate Weapon Payload 2	2 AAMs	8 AAMs
Structural Design Load Factor	3 G's	5 G's
Combat Turnaround Time	< 6 hr.	< 2 hr.
Avionics	Comm, Nav, & Ident	CNI + Radar MTI & Spot Modes + EW Suite
Takeoff & Landing	8,000 ft. Runway SLS	Carrier Suitable
Thermal Protection / Cooling	Must Be Addressed	
Loiter	10-min @ 5,000 ft.	
Sustained Turn	1.5 G @ M≥4.0, Alt≥60,000 ft	
Transient Turn	3.0 G @ M≥4.0, Alt≥60,000 ft	
Time-to-Target	To be Determined	

Table II: Carrier Compatibility Requirements [2]

Requirement	Value
RFP Imposed	
Maximum Gross Weight	75,000 lb.
Maximum Landing Weight*	55,000 lb.
Maximum Landing Speed	135 kts.
Minimum Thrust to Weight Ratio	0.5
Maximum Wing Span	64 ft.
Maximum Length (tow bar – aft end)	46 ft.
Maximum Height (Folded)	18.5 ft.
Other, Derived Requirements	
Requirement	**Value**
Maximum Take-Off Speed	150 kts.

* With 30 min fuel, 5% Reserves, & Design Payload

Four scenarios come to mind that illustrate the effect of wide ranging requirements, and the discontinuous nature of the responses. These scenarios, with the typical configurations that they drive are shown in Table III.

Baseline System – The baseline vehicle was designed to fulfill the minimum mission requirements with the maximum affordability. In most cases the Requirements and Technologies chosen were the lowest in technology level and represented the lowest risk. This produced a relatively simple fixed geometry vehicle with a turbo/ramjet propulsion system.

Long Range System- The long-range alternative is similar to the baseline system, except that the mission radius was increased to 1500-nm. The remaining constraints for payload and other mission capabilities remained the same. This forced the vehicle to cruise at a higher Mach number. The higher Mach number, thereby, dictated the inclusion of a Scramjet propulsion cycle and more complicated thermal protection systems.

Fifteen-Minute Time-to-Target System – The third system illustrated was one where the time-to-target request was fixed at a low value, less than 15-minutes to 750-nm. This necessitated the increase of the thrust to weight ratio. Further, because the thrust to weight ratio needed to be significantly higher than the other alternatives, the use of rocket propulsion was explored.

Carrier Compatible System – The RFP specified that a carrier compatible system needed to be studied, if for no other reason than to determine the mission tradeoffs required to force the vehicle to be carrier compatible. The additional constraints that operations in a carrier environment placed upon the vehicle produced a vastly different system compared to the previous alternatives. The required technology was significantly more complex, such as variable geometry, and many systems had to be considered beyond the State of the Art (SOA).

SYSTEM LEVEL TECHNOLOGY IDENTIFICATION & TECHNOLOGY ALTERNATIVE CREATION (STEP 3) – Once the requirements Matrix of Alternatives has been created. A technology Morphological Matrix can be created. The creation of such Morphological Matrices is discussed in detail in several papers by Kirby and Mavris **[3, 4, and 5]**.

Based on this Technology Morphological Matrix, several alternative technological combinations can be created. These can either be grouped and evaluated manually by the engineer, or they could be automated and assessed by a genetic algorithm for instance. The benefit of automation is in dealing with the combinatorics involved with a large number of technologies. If an automated system is used, some method must be incorporated to insure that incompatible technological combinations are removed. A portion of the HSF Technology Morphological Matrix is given in Figure 4. The technology Morphological Matrix is a combination of both vehicle design concepts and technologies. The combination of the requirements and technology Morphological Matrices allows the formation of different scenarios and concepts.

Requirement	Alternatives					
	1	2	3	4	5	6
Cruise Mach Number	4	5	6	7	8	
Mission Radius (nm)	750	850	1000	1200	1500	
Max Speed @ Sea Level	400	500	630			
Design Weapon Payload	1	2	4	6	8	
Structural Design Load Factor (G's)	3	4	5			
Combat Trunaround Time (hr)	6	4	2			
Avionics	CNI	CNI + Radar	CNI + EW	CNI+Radar+ EW		
Takeoff & Landing	8,000 ft	Carrier Compatible				
Time-to-Target (min)	10	15	20	25	30	40

Figure 3: HSF Requirements Matrix of Alternatives (Baseline is Shaded)

Table III: Specific HSF Requirements Scenarios

Requirement	Alternative			
	1	2	3	4
Cruise Mach Number	4	7.5	7	4
Mission Radius (nm)	750	1500	750	750
Takeoff & Landing	8,000 ft	8,000 ft	8,000 ft	Carrier Compatible
Time-to Target	25 min	25 min	<15 min	25 min
Resulting Vehicle	Turbo/Ramjet	Turbo/Ramjet/ Scramjet	Rocket/Ramjet	Turbo/ramjet/Vari able Geometry

Concepts			Alternatives 1	2	3	4	5	6	7
Aerodynamics		Lift	wing	body	wing and body				
		Control	surfaces	moving wings	panels	energy			
		Thrust	integrated	partially integrated	non-integrated				
	Wing	Wing Type	full Delta wing	small Delta wing	tails	wing and tails	swing wing	Drooped Wing	none
		Wing Cross Section	traditional	diamond	almond	biconvex			
		Wing Location	tail	canard	center	multiple			
	Body	Body Type	wave rider	partial	Non Waverider				
		Body Cross Section	square	triangle	ellipse	crescent	other		
		Body Shape	wedge	cone	square	other			
		Nose	blunt	sharp	spatula	spike			
		Other Surfaces	pitch control	yaw control	roll control	mutliple	none		
		Other Surface Location	tail	canard	center	top	multiple		
		Variable Geometry	wing tips	all wing	none				
Propulsion	Engine Cycles	Boost	Pulsejet	Turbojet	Pulse Detonation Engine	Rocket			
		Cruise	Pulse Detonation Engine	Ramjet	SCRAMJET				
		Fuels	JP4	JP4 with high temperature additives	methane	hydrogen	Solid Rocket Fuels	JP4 / Hydrogen	JP4/ Methane
Structures	Airframe	Concept	Hot Structure	Insulated Structure	Actively Cooled Structure				
		Material	Metal Matrix Compostie	Ceramic Matrix Composite	Advanced C-C (ACC)	Superalloy	Aluminium Alloy	Titanium Alloy	
		Structural Panels	Tubular	Beaded web corrugation	Truss-core web corrugation				
	L.E. and Nose Cap	TPS	Active Fuel Cooling	Active Dedicated Fluid Cooling	Passive Cooling (Material)				
		Material	SiC/Reinforced C-C (RCC)	Advanced C-C (ACC)	UHT Ceramics (e.g. Rh + Ir)	Titanium Alloy			
	Body Skin	TPS	Active Fuel Cooling	Active Dedicated Fluid Cooling	Passive Cooling (Material)				
		Material	Metal Matrix Compostie	Ceramic Matrix Composite	Superalloy	Aluminium Alloy	Titanium Alloy	C/SiC	SiC/SiC
	Wing Skin	TPS	Active Fuel Cooling	Active Dedicated Fluid Cooling	Passive Cooling (Material)				
		Material	Metal Matrix Compostie	Ceramic Matrix Composite	Superalloy	Aluminium Alloy	Titanium Alloy	C/SiC	SiC/SiC
	Fuel	Concept	External Cryogenic	Integral Cryogenic	Non Integral Cryogenic	Flexible Bag	Stiffened Cell		
	Engine Wall	Engine Cooling	Heat Pipe	Non Heat Pipe	Lip Heat Dissipation Fins (e.g. Cu, Be)				
		Concept	Frame-stiffened Honeycomb	Deep-core Honeycomb					
	TPS	Concept	Reusable Surface Insulation (Sp. Sh.)	Advanced Ceramic (X-34, Alumina Enh. Therm Barrier)	Advanced Metallic (X-33, Superalloy Honeycomb)	Rigid ceramic tiles	Ceramic shingle	Metallic shingles	Multiwall TPS panels (e.g. Ti)
Stability & Control	Control Concept	Stability	Static Stability	Relax Static Stability					
		Control	Conventional Control	Thrust Vectoring	Smart Structure				
	Control Surfaces	Longitudinal Control Surface	Elevator	Moveable Horizontal Tail	All-moving wing (symmetric deflection)	Body flaps	Canard		
		Directional Control Surface	Rudder	Moveable Vertical Tail	All-moving wings (differential deflection)	Reaction control jets	Flaps		
		Lateral Control Surface	Aileron	Flaps	All-moving wings (differential deflection)	Reaction control jets			

Figure 4: HSF Concept Configuration and Technology Matrix of Alternatives (Shaded Boxes indicate the Baseline)

ALTERNATIVE CONCEPT SIZING AND SYNTHESIS (STEP 4) – To evaluate which technology combinations are feasible and viable for different sections of the requirements space a baseline configuration must be selected, synthesized, and sized. Depending on the vehicle, codes are readily available for this task. However, for parametric investigations of wide requirements spaces where different classes of vehicles may be suitable a lower level of fidelity, higher abstraction tool was desired. As the design progressed it was possible to incorporate higher fidelity, vehicle class specific tools. Further, to assist in visualization and to minimize the time associated with the initial selection, a meta-model approach was implemented. The initial tools are described below:

High Level Concept Exploration and Sizing - Because the effects of the varying requirements can only be determined by sizing the aircraft to meet these objectives, it is necessary to use some form of sizing and synthesis code. The implementation used in this method is of lower fidelity/higher abstraction than typical vehicle class codes. In higher fidelity, vehicle class specific codes the discontinuous nature of the responses to requirements, such as time-to-target for instance, requires that multiple propulsion schemes be addressed. Therefore, a code that was designed to work with airbreathing systems, with moderate I_{sp}'s, would have difficulty when dealing with rocket based systems. This is illustrated in Figure 5. The initial implementation used was in the form of a Microsoft Excel spreadsheet. The spreadsheet utilizes physics and energy based methods **[6]**, and manipulates Equation 1 to map each of the requirements found in the RFP to thrust and wing loading.

$$[T-(D+R)]V = W\frac{dh}{dt} + \frac{W}{2g_0}\frac{dV^2}{dt} \qquad (1)$$

Where T is thrust, D and R are drag components, V is velocity, W is weight, h is altitude, t is time and g_0 is the acceleration due to gravity.

This formulation allows the requirements and technologies to be viewed in a continuous manner with respect to the sizing program. As more information becomes available and a vehicle class is selected, greater fidelity tools may then be employed. The low fidelity implementation was designed to perform the basic HSF mission profile. The mission profile for the notional HSF is shown in Figure 6.

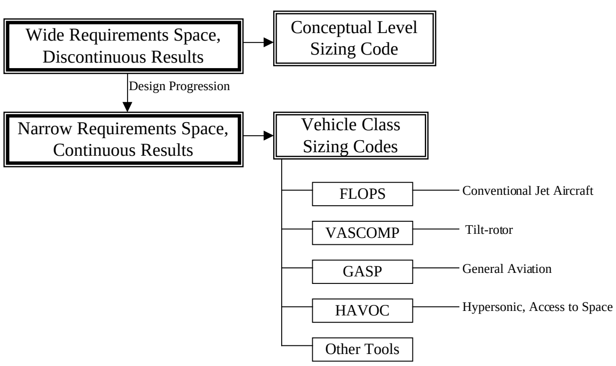

Figure 5: Vehicle sizing Tool Progression

A benefit in using a higher level of abstraction/problem formulation such as described above is that the engineer can easily look at many different vehicles without having to perform exhaustive high fidelity analysis. The trade off is that the accuracy and fidelity of the results for this sizing is lower than it would be using a higher fidelity code such as FLOPS; which is not designed to size hypersonic vehicles, and would have to be modified to accept physics-based meta-models. The engineer has many options when addressing this shortcoming, including the use of probabilistics to assign a range of uncertainty to the values produced by the low fidelity implementation.

Meta-model Implementation - In order to simplify the computational burden for the requirements study, and thereby to simplify the design of the selected technology combination, a meta-model approach, using a Response Surface Methodology (RSM), was implemented. This approach also allows for easy visualization of the system and the requirements space, and the effect that a change in requirements has on the characteristics of the sized vehicle. This is equivalent to combining all of the prediction profiles, i.e. the top-level requirements vehicle design variables, and technology k-factors in Figure 1. This is shown in Figure 7. A cursory glance at the response of the system to several points in the requirements space indicated that a linear model would probably not capture the true nature of the HSF's design space variability.

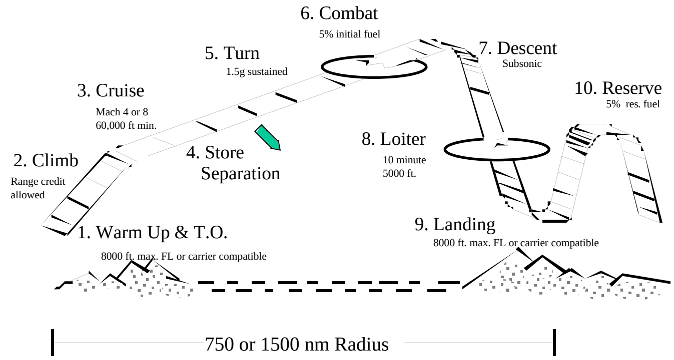

Figure 6: HSF Notional Mission Profile

Another of the problems associated with trying to fit a highly complex set of system behaviors to a simple quadratic equation is the fact that in certain regimes the difference between the actual system response and the model can be significant. While most of the responses tracked in the requirements analysis, accurately fit the standard three-level Response Surface Equation (RSE), several had low goodness of fit, and errant results at the extreme end of the DoE range. Since the capability for higher level DoEs with many variables is limited, a variable transformation was required to improve fit and performance at extreme ranges. The statistical program used, *JMP*, is capable of estimating the best transformation to employ.

Higher Fidelity Tools – Though lower fidelity tools can give the engineer a good feel for how the technological alternatives look when mapped to the requirements space, they are not sufficient to get a truly accurate representation of the vehicle. A higher fidelity version of the spreadsheet was implemented for further sizing of the selected concepts. This was coupled with higher fidelity propulsion, aerodynamics, and structural analysis. The implementation of several of these is described in References **[7, 8, 9]**.

EVALUATION OF TECHNOLOGICAL ALTERNATIVES (STEP 5) – With the sized technology alternatives, it is possible to evaluate their feasibility in the requirements space. It is here that the meta-model approach comes in handy. By using the RSM method described in Ref [3, 4, 5], it is possible to get a graphical representation of the requirements space. In this paper, this is done by examining the standard design space with the requirements placed as constraints or contours on the design space. These graphical representations were created using the capabilities of the JMP software **[10]**.

Requirement Trade-Offs – In many cases the requirements sensitivity study would be performed by the engineer as part of a risk assessment study. However, there are cases where the requirements study can be used to determine which specific point in a requirements space the system is to fall. This can be performed using Integrated Product and Process Development (IPPD) methods including the Quality Function Deployment (QFD), and by placing the requirement and system alternatives in a Pugh or weighted decision matrix. The selection can then be made through either a qualitative technique, as implemented with the HSF, or a quantitative technique such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) **[3]**.

RESULTS

The uniqueness of the design of a HSF and the wording of the RFP necessitated that the requirements analysis be performed to determine the specific requirement combinations and the specific technology combinations that would be used on the HSF. Both the unconstrained and constrained design space was evaluated.

VEHICLE TECHNOLOGIES AND THE RESULTING DESIGN SPACE - The four concept systems examined illustrate the effect of both extreme changes in a continuous requirements space, and the effect of an open and misbehaved requirements space. It is, therefore, helpful to evaluate the effect of the cruise mach number and mission radius on critical vehicle properties.

System Response without Constraints – The baseline system provides many opportunities to view the effect of changing design variables. In this case, the requirements space is taken to be totally wide open. This allows the engineer to quickly view the response of the system to specific changes in design variables. In the case of the HSF two of the most helpful are the effect that changing cruise Mach number and mission radius have on the time-to-radius and gross weight of the vehicle.

The RFP stated that the HSF was to be designed to counter “time-critical, high value” targets. However, the RFP gave no definition as to what constituted a time-critical target. It was up to the engineer to determine what an acceptable time-to-target would be for the HSF. Therefore, the effect that changes in the Cruise Mach Number and mission radius had on the time to mission radius are of interest. Figure 8 illustrates this at a specific thrust to weight and wing loading value.

The other area where the RFP stated a desire, but did not give a specification was with respect to vehicle affordability. In this case, the methods used to create the meta-models did not directly address vehicle cost. However, historically the cost of a vehicle has been a function of both the weight and the complexity. Therefore, it was useful to study the effect of cruise Mach number and mission radius on the gross weight. Figure 9 illustrates the effect of differing mission radii and cruise Mach numbers on the vehicle gross weight. The aspect of complexity was dealt with in a qualitative manner.

The results clearly indicated that while increasing the cruise Mach number had a positive effect on reducing the time-to-target, it also had the effect of significantly increasing the gross weight and complexity of the aircraft. This is extremely useful if decisions about specific tradeoffs in requirements need to be made by the engineer.

Application of Constraints – The addition of the requirement base constraints has the effect of significantly reducing the feasible space. The two constraints with the greatest effect are changing from the land-based aircraft to a carrier compatible system, and the inclusion of specific time-to-target requirements. Changing either of these requirements has a significant effect on the technology combination required. The four specific examples were studied with their constraints in place.

The baseline system, with specific constraints on flight performance parameters, produces a much smaller feasible design space, as expected, when compared to the unconstrained space. Figure 10, on page 12 shows the remaining design space for the Mach 4 class, baseline vehicle.

The unshaded portion of the chart illustrates the feasible design space. This gives the engineer a visual reference to the amount of feasible space the specific combination of technologies and design variables produces. The design variables or factors (X’s) are given at the top of the figure, with the baseline inputs to the right of the variable name. To the left of the design variable names is the selection of which design variables are shown on the x- and y-axis. Below the design variables are the responses (Y’s). The responses include typical performance metrics. In addition to the current values of the responses, constraint values are given. These allow the engineer to both block off a portion of the design space, and to display the topography of the meta-model visually. Both of these are used in determining the best combination of technologies to meet a specific requirement combination.

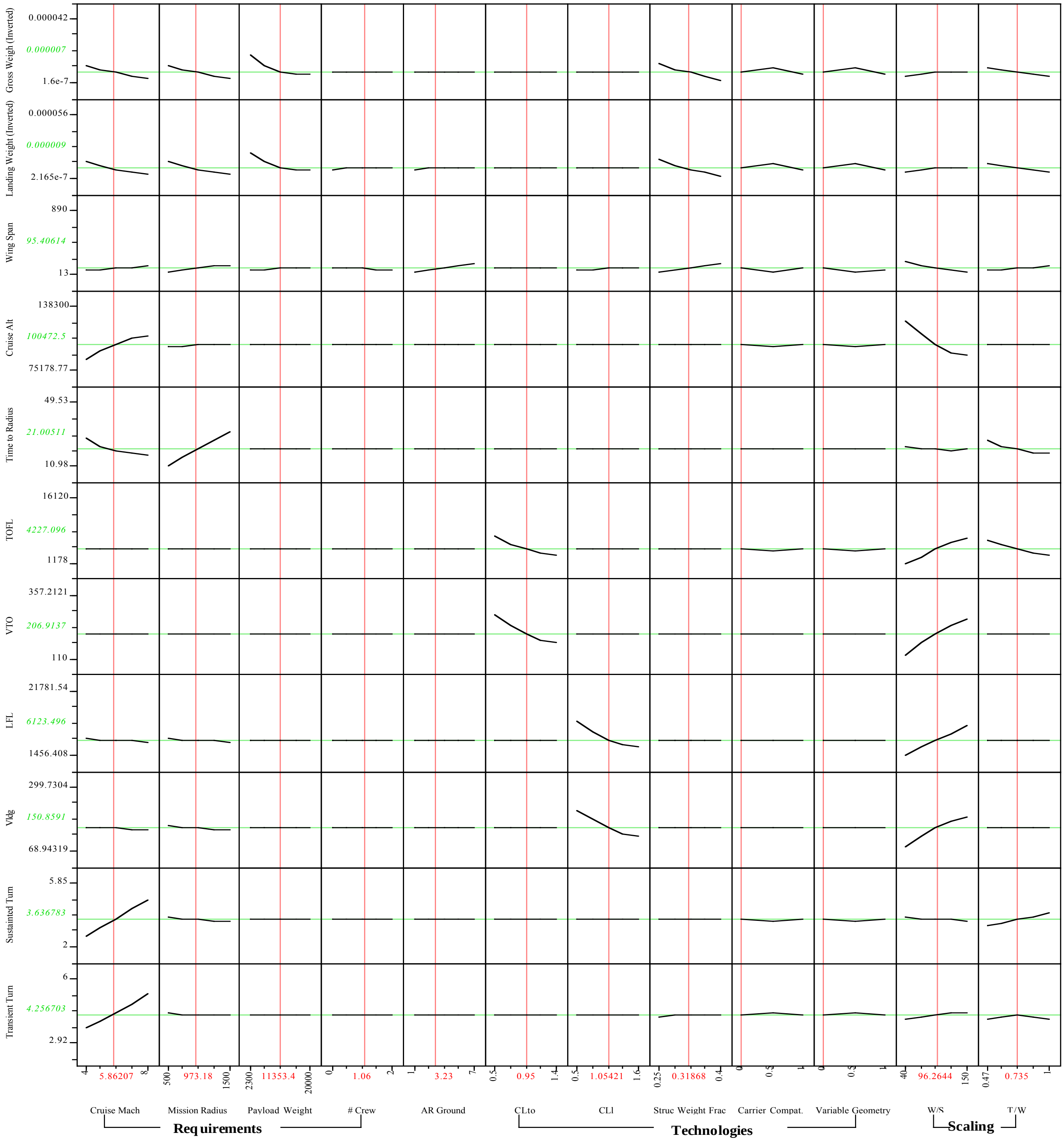

Figure 7: Prediction Profiles of Requirements and Design Space

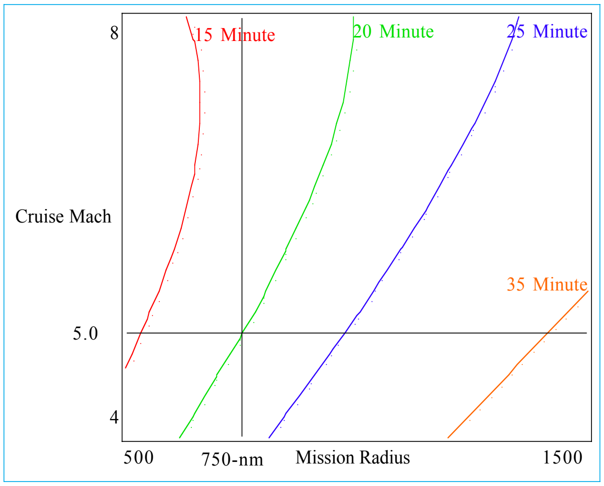

Figure 8: Effect of Mission Radius and Cruise Mach Number on Time to Target.

Note: The areas above and left of the time-to-target lines indicate space where the cruise Mach number and mission radius combination result in a time-to-target of less than the specified times. Further, the increase in time-to-target with higher cruise numbers at low radii is because of the increased demand from climb and cruise, which reduced the average flight Mach number.

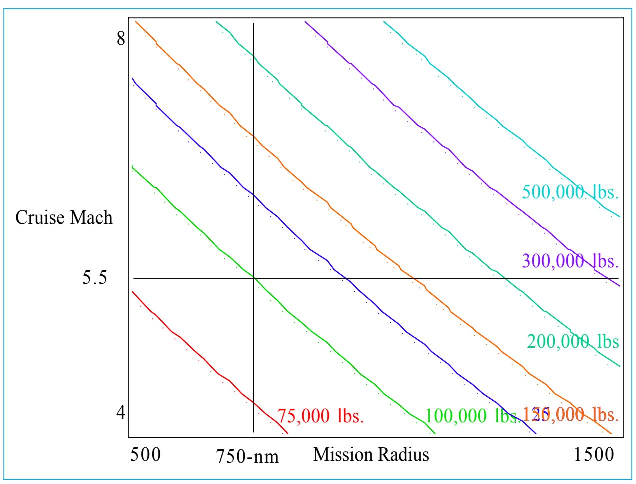

Figure 9: Effect of Mission Radius and Cruise Mach Number on Vehicle Weight

Note: The space below and to the left of the gross weight lines is the area in the design space where the gross weight of the vehicle is less than that indicated on the line.

The first alternative explored, after the baseline, employed the same time-to-target requirements, but was designed to meet the desired mission radius of 1500-nm. This necessitated a higher cruise Mach number, as shown in Figure 11, on page 12. This requirements change necessitated a different technology selection. This produces a significantly different vehicle.

First, a cruise Mach number above six dictates the use of a Scramjet in the propulsion system. This not only adds a less proven cycle for cruise, but also dictates that another propulsion cycle be added to the vehicle. Further, the increased cruise Mach number dictates a more complex thermal protection system, which increases cost. For instance, since the temperature of the flow increases with the cube of the velocity **[11]**, the increased Mach number places increasingly higher heating loads on the aircraft. While many scenarios increase the complexity of the aircraft, other scenarios may eliminate the remaining design space.

The reduced time-to-target scenario shown in Figure 12, on page 13 illustrates the lack of remaining design space. In this case, the time-to-target was decreased to such a value, less than 15-minutes, yielding insufficient thrust to weight for the turbine-powered vehicle. One option is to use a rocket-based propulsion system. However, the specific loiter requirement virtually eliminates the ability to use rocket motors. A higher aggregate I_{SP} solution would have to be used. To achieve this a combination rocket and airbreathing low speed propulsion system could be implemented. However, because of the necessity of recovering and reusing the HSF, which dictated a higher weight structure, there were no rocket combinations that produced converged solutions. This could be addressed with expendable boosters or newer, beyond SOA structural or rocket technologies.

In the case of the carrier compatible alternative, the same method above can be used to identify what technology combinations, if any produce a carrier compatible aircraft that also meets the remaining threshold requirements. In the case of this study, the technologies selected did not produce a combination that provided a feasible and viable design space. To meet the carrier requirements the takeoff and landing speeds had to be reduced. This required a relatively high C_{Lmax}. However, because of the relatively poor low speed lift characteristics of the delta wing, and attitude constraints when dealing with carrier operations, a swing-wing was required. This increases aspect ratio and allows for the use of high lift devices. It also increases the wing span during shipboard operations. This forced the wing span to violate the carrier constraint. To address this it was necessary to design the carrier compatible HSF to specifications below the threshold values, or identify significant weight saving technologies.

Therefore, it was necessary to analyze which requirements must be relaxed to fulfill the carrier compatibility requirement of the RFP. The results of this analysis showed that both the range and the payload would have to be reduced to produce an aircraft that was carrier compatible with technologies selected from the technology morphological matrix. The reduced mission capability requirements are given in Table IV, and the resulting design space is shown in Figure 13, on page 13.

Table IV: Required Capability Reductions to Meet Carrier Compatibility

Mission Requirement	Threshold Value	Reduced Value
Mission Radius	750 nm	500 nm
Payload	2-2,250 lb. Weapons	1-2,250 lb. Weapon

CONCLUSION

In many instances, of which the design of a HSF is an example, there is the need for an organized method to determine not only which vehicle best fits the requirements set forth, but also which combination of systems produces the best design in a changing requirements environment. Further, there are many instances where the requirements space is not fully defined during the conceptual and preliminary design stages of a new program. Therefore, it is even more critical that such a methodology be employed, both to maximize the capability of the vehicle system, and to minimize the chance that a requirements change or refinement will endanger the ability of a program to fulfill its goals. While it may not be possible to design a vehicle that satisfactorily encompasses the entire requirements space, the engineer has the ability using the methodology to determine where in the space the vehicle, and its corresponding technology combination is either not feasible or viable.

The method described in this paper allows for a straightforward evaluation of multiple technological alternatives and requirements spaces that produce continuous, discontinuous, or hybrid responses. Further, the framework allows the engineer to increase the level of fidelity in his or her tools as the design progresses. It provides a rigorous method for requirements and concept exploration, design and selection of an aerospace system. The application of the methodology to a HSF illustrates the effectiveness of the methodology in addressing complex systems with evolving requirements.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CNI: Command, Navigation, & Identification

DoE: Design of Experiments

EW: Electronic Warfare

HSF: Hypersonic Strike Fighter

IPPD: Integrated Product and Process Development

I_{SP}: Specific Impulse

Morphological Matrix: A matrix listing alternative technologies that may be used in different subsystems of a complex system design.

MTI: Moving Target Indicator

QFD: Quality Function Deployment

Requirements Space: An n-dimensional space, where each dimension is represents a specific variable requirement. The space is bounded by specific upper and lower requirement values. The requirements space does not have to be continuos.

Requirements Morphological Matrix: An extension of the Morphological Matrix in which requirements are listed specific alternative values or ranges.

RFP: Request for Proposal

RSE: Response Surface Equation

RSM: Response Surface Methodology

SLS: Sea Level Standard

SOA: State of the Art

TIF: Technology Impact Forecasting

TIES: Technology Identification Evaluation and Selection

TOPSIS: Technique for Order Preference by Similarity to Ideal Solution

T/W: Thrust to Weight Ratio

W/S: Wing Loading

Horiz	Vert	Factor	Current X	Grid Density
_	_	Cruise Mach	4	
_	_	Mission Radius	750	
_	_	Payload Weight	4500	
_	X	T/W	0.643308	
_	_	# Crew	0	
X	_	W/S	68.668555	
_	_	AR Ground	2	
_	_	CLto	0.645	
_	_	CLl	0.645	
_	_	Struc Weight Frac	0.35	
_	_	Carrier Compat.	0	
_	_	Variable Geometry	0	

Response	Contour	Current Y	Lo Limit	Hi Limit
Gross Weight (I	0.0000133	0.0000217	0.0000133	¥
Cruise Alt	60000	96520.121	60000	¥
Time to Radius	25	24.798893	¥	25
TOFL	8000	4865.1784	¥	8000
VTO	500	211.39771	¥	¥
LFL	8000	7704.5418	¥	8000
Vldg	500	169.83809	¥	8000
Sustainted Turn	1.5	2.4814404	1.5	¥
Transient Turn	3	3.3223091	1.5	¥

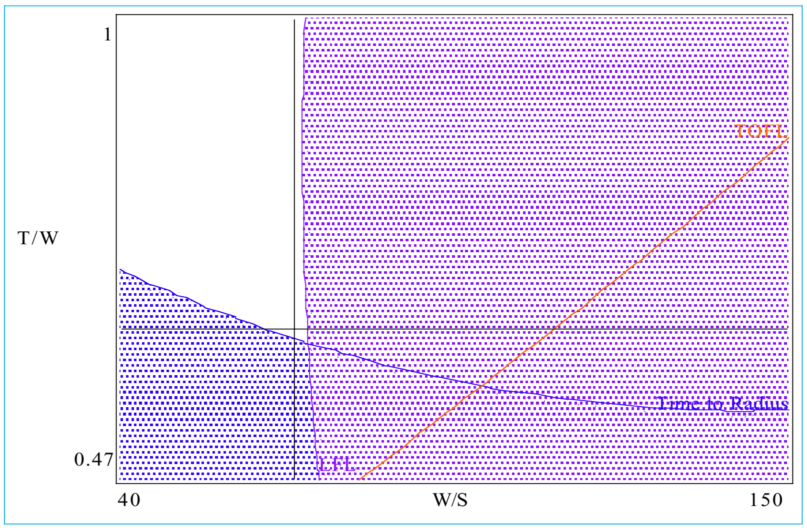

Figure 10: Baseline Mach 4 Class Hypersonic Strike Fighter

Horiz	Vert	Factor	Current X	Grid Density
_	_	Cruise Mach	7.1179487	
_	_	Mission Radius	1500	
_	_	Payload Weight	4500	
_	X	T/W	0.8995565	
_	_	# Crew	0	
X	_	W/S	85.692308	
_	_	AR Ground	2	
_	_	CLto	0.645	
_	_	CLl	0.645	
_	_	Struc Weight Frac	0.35	
_	_	Carrier Compat.	0	
_	_	Variable Geometry	0	

Response	Contour	Current Y	Lo Limit	Hi Limit
Landing Weight	¥	-0.000003	¥	¥
Wing Span ^-0.8	¥	0.0266525	¥	¥
Cruise Alt	60000	111739.91	60000	¥
Time to Radius	25	24.903713	¥	25
TOFL	8000	4319.3711	¥	8000
VTO	¥	237.73963	¥	¥
LFL	8000	7810.9345	¥	8000
Vldg	¥	171.73146	¥	¥
Sustained Turn	1.5	4.4693978	1.5	¥
Transient Turn	3	4.7544648	3	¥
Gross Weight (I	¥	-5.759e-7	¥	¥

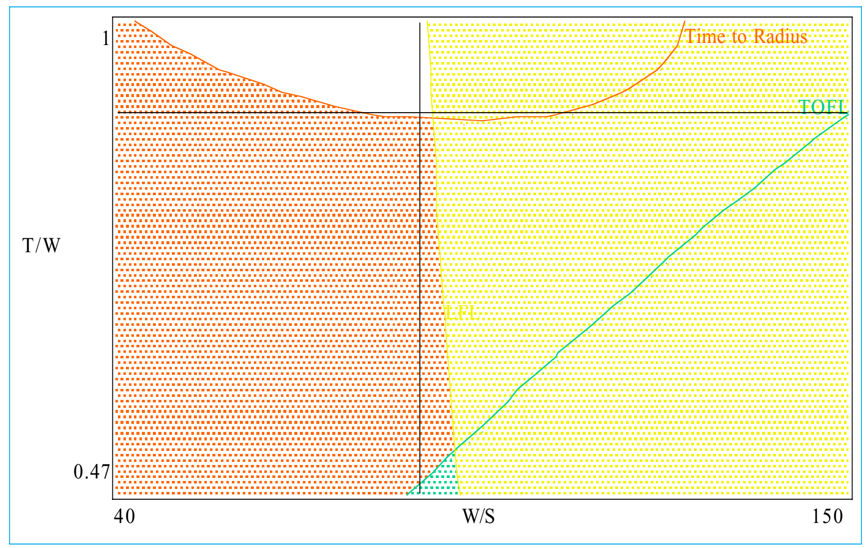

Figure 11: Long Range Mission Alternative

Horiz	Vert	Factor	Current X	Grid Density
_	_	Cruise Mach	7.1179487	
_	_	Mission Radius	750	
_	_	Payload Weight	4500	
_	X	T/W	0.8995565	
_	_	# Crew	0	
X	_	W/S	85.692308	
_	_	AR Ground	2	
_	_	CLto	0.645	
_	_	CLl	0.645	
_	_	Struc Weight Frac	0.35	
_	_	Carrier Compat.	0	
_	_	Variable Geometry	0	

Response	Contour	Current Y	Lo Limit	Hi Limit
Landing Weight	¥	0.0000079	¥	¥
Wing Span ^-0.8	¥	0.0450165	¥	¥
Cruise Alt	60000	109647.91	60000	¥
Time to Radius	12	13.139982	¥	12
TOFL	8000	4316.1019	¥	8000
VTO	¥	237.88117	¥	¥
LFL	8000	8939.2398	¥	8000
Vldg	¥	183.37035	¥	¥
Sustained Turn	1.5	4.7975276	1.5	¥
Transient Turn	3	4.8389289	3	¥
Gross Weight (I	¥	0.0000005	¥	¥

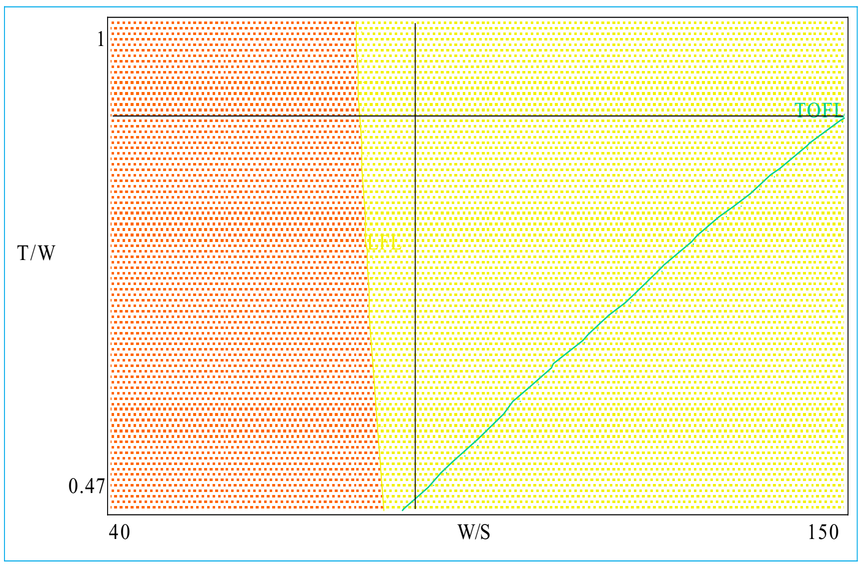

Figure 12: Time Critical Mission (<15 Minute Time to Target)

Horiz	Vert	Factor	Current X	Grid Density
_	_	Cruise Mach	4	
_	_	Mission Radius	500	
_	_	Payload Weight	2300	
_	X	T/W	0.5	
_	_	# Crew	0	
X	_	W/S	73	
_	_	AR Ground	6	
_	_	CLto	1.5	
_	_	CLl	2	
_	_	Struc Weight Frac	0.35	
_	_	Carrier Compat.	1	
_	_	Variable Geometry	1	

Response	Contour	Current Y	Lo Limit	Hi Limit
Gross Weight (I	0.0000133	0.0000263	0.0000133	¥
Landing Weight	0.0000182	0.0000351	0.0000182	¥
Cruise Alt	60000	94837.776	60000	¥
Time to Radius	25	21.505303	¥	¥
TOFL	8000	3077.9664	¥	8000
VTO	150	149.30966	¥	150
LFL	8000	4929.7445	¥	8000
Vldg	135	122.79612	¥	135
Sustained Turn	1.5	2.143253	1.5	¥
Transient Turn	3	3.2894914	3	¥
Wing Span^-0.8	0.035454	0.0383026	0.035454	¥

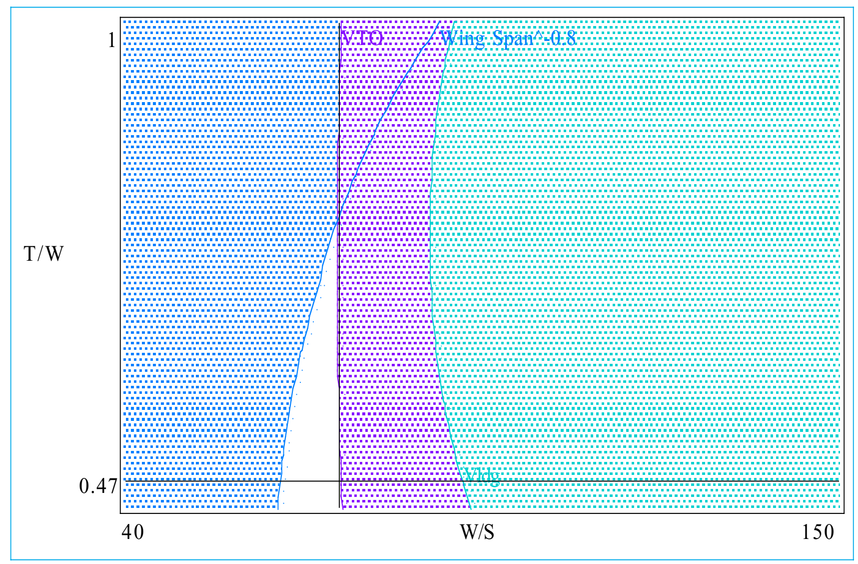

Figure 13: Carrier Compatible Aircraft, Reduced Mission Radius and Payload